INL/EXT-05-00543

I-NERI Quarterly Technical Progress Report

April 1 to June 30, 2005

Project 2003-013-K – Development of Safety Analysis Codes and Experimental Validation for a Very High Temperature Gas-Cooled Reactor

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Idaho National Laboratory

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I-NERI QUARTERLY TECHNICAL PROGRESS REPORT

Project Number and Title: Project 2003-013-K, Development of Safety Analysis Codes and Experimental Validation for a Very-High-Temperature Gas-Cooled Reactor

Lead U.S. Investigating Organization: Idaho National Engineering and Environmental Laboratory (INEEL)
U.S. Principal Investigator: Dr. Chang Oh

Lead Collaborating Investigating Organization: Korea Advanced Institute of Science and Technology (KAIST)
Lead Collaborating Principal Investigator: Prof. Hee Cheon NO

Other Collaborating Organizations:
Profs. John Lee, William Martin, and James Holloway, University of Michigan
Prof. Jong Kim, KAIST
Prof. Goon Cherl Park, Seoul National Laboratory (SNU)

Reporting Period: April 1, to June 30, 2005

Research and Development Areas: Next-generation reactor system

Project Status Summary

The objective of this Korean/United States/laboratory/university collaboration is to develop new advanced computational methods for safety analysis codes for very-high-temperature gas-cooled reactors (VHTGRs) and numerical and experimental validation of these computer codes**.** This study consists of five tasks for FY-03: (1) development of computational methods for the VHTGR, (2) theoretical modification of aforementioned computer codes for molecular diffusion (RELAP5/ATHENA) and modeling CO and CO_2 equilibrium (MELCOR), (3) development of a state-of-the-art methodology for VHTGR neutronic analysis and calculation of accurate power distributions and decay heat deposition rates, (4) reactor cavity cooling system experiment, and (5) graphite oxidation experiment.

Second quarter of Year 3

- Prof. NO and Kim continued Task 1. As a further plant application of GAMMA code, we conducted two analyses: IAEA GT-MHR benchmark calculation for LPCC and air ingress analysis for PMR 600MWt. The GAMMA code shows comparable peak fuel temperature trend to those of other country codes. The analysis results for air ingress show much different trend from that of previous PBR analysis: later onset of natural circulation and less significant rise in graphite temperature.

- Prof. Park continued Task 2. We have designed new separate effect test device having same heat transfer area and different diameter and total number of U-bands of air cooling pipe. New design has smaller pressure drop in the air cooling pipe than the previous one as designed with larger diameter and less number of U-bands. With the device, additional experiments have been performed to obtain temperature distributions of the water tank, the surface and the center of cooling pipe on axis. The results will be used to optimize the design of SNU-RCCS.

- Prof. NO continued Task 3. The experimental work of air ingress is going on without any concern: With nuclear graphite IG-110, various kinetic parameters and reaction rates for the C/CO2 reaction were measured. Then, the rates of C/CO2 reaction were compared to the ones of C/O2 reaction. The rate equation for C/CO2 has been developed.

- INL added models to RELAP5/ATHENA to cacilate the chemical reactions in a VHTR during an airingress accident. Limited testing of the models indicate that they are calculating a correct special distribution in gas compositions.

- INL benchmarked NACOK natural circulation data.

- Professor Lee et al at the University of Michigan (UM) Task 5. The funding was received from the DOE Richland Office at the end of May and the subcontract paperwork was delivered to the UM on the sixth of June. The objective of this task is to develop a state of the art neutronics model for determining power distributions and decay heat deposition rates in a VHTGR core. Our effort during the reporting period covered reactor physics analysis of coated particles and coupled nuclear-thermal-hydraulic (TH) calculations, together with initial calculations for decay heat deposition rates in the core

Project Organization:

This project is organized and managed by Chang Oh at the INEEL with collaboration of Professor Hee Cheon NO at the Korea Advanced Institute of Science and Technology (KAIST). Tasks 1 and 3 are performed by KAIST professors, Hee Cheon NO and Jong Kim, Hee NO serves as the program manager for the Korean side. Task 2 is performed by Professor Goon Cherl Park at Seoul National University. Task 4 is performed by Chang Oh, Cliff Davis, Richard Moore and Larry Siefken at the INEEL. Task 5 is performed by Professors John Lee, William Martin, and James Holloway. FY-03 tasks involve Task 1,2,3,4, and 5.

Narrative:

Task 1:

CFD TH Code Development (KAIST)

Task Status and Significant Results

The objective of this task is to develop an analysis tool for thermal-hydraulic transport processes in VHTGR. Thermal hydraulic models to be incorporated in the numerical tool include (1) diffusion of gas species involved, (2) convective mass, momentum, and energy, (3) energy conduction and radiation transport thorough graphite, core barrel, reactor vessel, concrete, and boundary, and (4) heat release by fission and decay heat.

In PMR 600MWt, helium at 490^{o}C enters the prismatic core through the inlet riser and exits at 850^{o}C, at a flow rate of 320

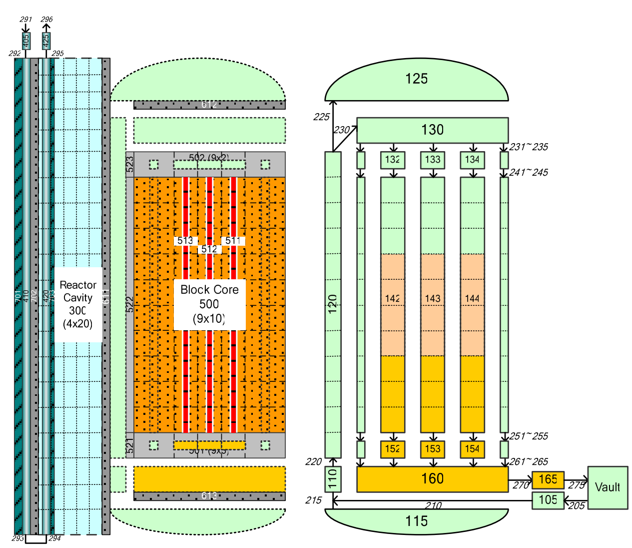

Fig. 1. GAMMA nodalization for PMR 600MWt: solid and reactor cavity (left) and fluid component

kg/s. **Fig. 1** show the GAMMA modeling of PMR and the helium flow paths at the right figure. The prismatic core and reactor cavity are modeled by 2-D geometry, and all the solid structures are modeled by 2-D geometry. For all the cavities or plenums, the radiation heat exchanges are considered. The air-cooling RCCS system is modeled using the 1-D pipe network for the air flow loop and the 3-D tube model for the cooling tubes.

First, in order to verify the GAMMA predictability for the system transient behavior, we performed the benchmark exercise for the low pressure conduction cooldown (LPCC) accident. **Fig. 2** shows the calculated fuel peak temperature and the results from other countries. The GAMMA code shows comparable temperature trend to those of other codes.

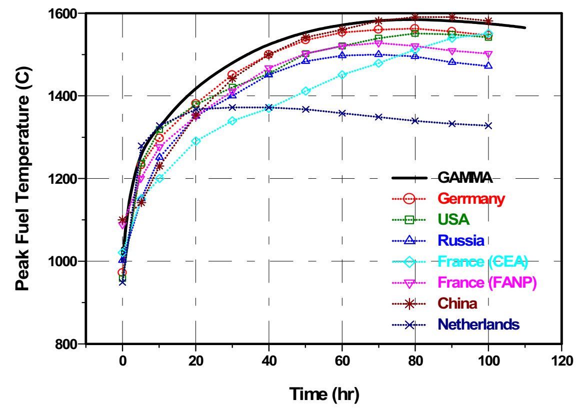

Fig. 2. IAEA GT-MHR benchmark calculation for the LPCC accident

For the air ingress analysis of PMR 600MWt, the air volume of 50,000 m^3 in a vault has been assumed. As shown in **Fig. 3**, the onset time of natural convection occurs at 570 hours, much delayed compared to that of previous PBR analysis. It is because of the lower equilibrium air concentration at the end of blowdown caused by the larger fluid volume ratio of the reactor coolant system to the vault. In addition, due to the large fluid volume inside the reactor vessel, the molecular diffusion process proceeds slowly and therefore the density of a gas mixture increases slowly, by delaying the onset time of a natural convection. As well, there is no significant rise in the core and reflector temperatures. It is mainly due to the higher ratio of the graphite volume to the surface area contacting with the oxygen.

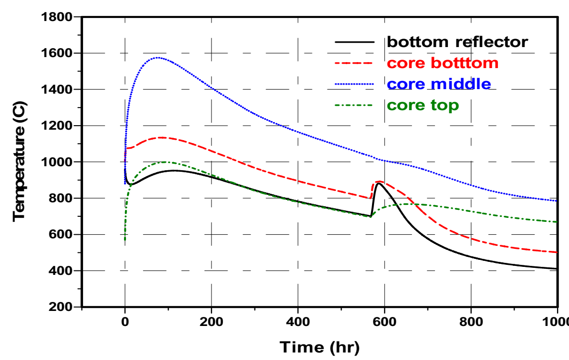

Fig. 3. Predicted axial temperatures at the fuel ring 1 (V_{air}=50,000 m^3)

Next Quarter Activities

- Documentation of GAMMA Manuals (user's manual, theoretical manual, and assessment report)

Issues/Concerns:

There are neither issues nor concerns. This task is right on schedule.

Task 2:

RCCS Separate Experiment (SNU)

Task Status and Significant Results

New separate effect test device simulates a quarter of the water tank in azimuthal direction and one third in radius direction as shown in **Fig. 4**. Compared to previous device, total number of U-bands of air cooling pipe was decreased from 16 to 11. In addition the diameter of air cooling pipe was enlarged from 63.5mm to 76.6mm to reduce the pressure drop. Other geometry such as height and width of water tank is preserved. Test results using the new separate effect test device show good agreement with previous experimental results.

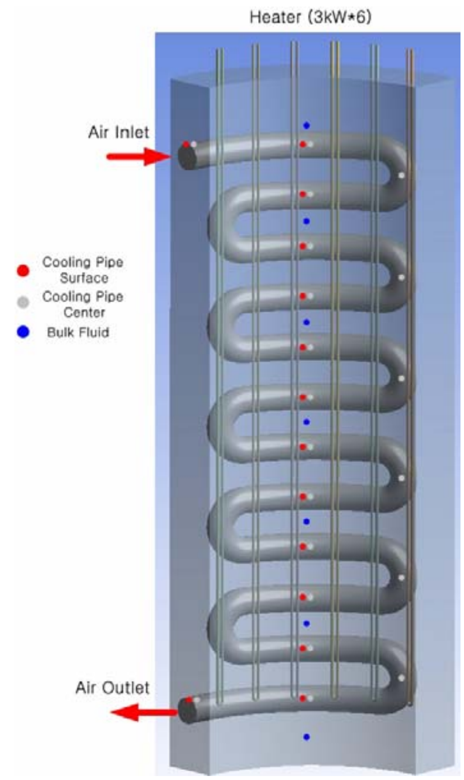

Fig. 4. Schematic diagram of the new separate effect test facility

The power for operating air blower was reduced more than 30% because the pressure drop was decreased due to the enlarged diameter of cooling pipe. It means that, if the diameter of cooling pipe increase, we can get more advantage in aspect of active cooling power. In this case, however, the capacity of water in the water tank is decreased and it can influence passive long term cooling of RCCS. Thus, the diameter and total number of U-bands of cooling pipe and water capacity should be considered synthetically.

Next Quarter Activities

- Validation for experimental results using CFX & MARS_GCR
- Design optimization of SNU RCCS

Issues/Concerns:

There are neither issues nor concerns.

Task 3:

Air Ingress Separate Experiment (KAIST)

Task Status and Significant Results

The objective of this task is to carry out graphite oxidation experiment, to determine the oxidation-limited model (chemical kinetics-limited, diffusion-limited or in-pore diffusion-limited model), and to develop measurement techniques of each species' concentration.

With nuclear graphite IG-110, we measured various kinetic parameters and reaction rates of the C/CO_2 reaction, which is induced by CO_2 gases generated from C/O_2 reaction. The reaction equation is written as follows.

$$C + CO_2 \rightarrow 2CO$$

This experiment was conducted in a temperature range between 600℃ and 1400℃, and in a CO2 mole fraction between 5 and 10 percent. The reaction rate was measured by gas concentration analysis method. **Fig. 5** shows the effect of temperature on the reaction rate obtained in this experiment. As a result, its activation energy was obtained as 295±8 kJ/mol and the order of reaction as 0.9. **Fig. 6** illustrates the comparison results between C/CO_2 reaction and C/O_2 reaction. This figure shows that the rate of C/CO_2 reaction is much smaller that the one of C/O_2 reaction below 1400℃. As the graphite temperature increases above 1400℃, the differences between them become smaller due to the mass diffusion effect of the C/O_2 reaction. Finally, we suggest the following rate equation for C/CO_2 reaction under our experimental conditions.

$$r(kg/m^3 s) = 5.7 \times 10^{-7} \exp\left(-\frac{295000}{R \cdot T}\right) \cdot (p_{CO2})^{0.9} \qquad (1)$$

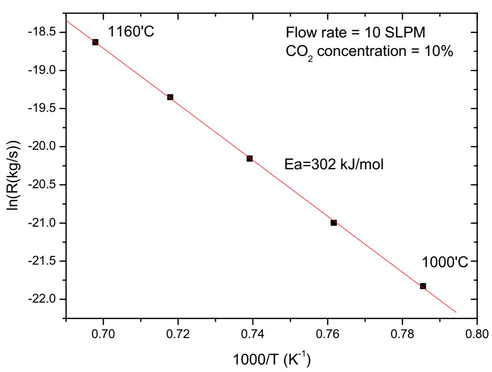

Fig. 5. Effect of temperature on the C/CO_2 reaction rate

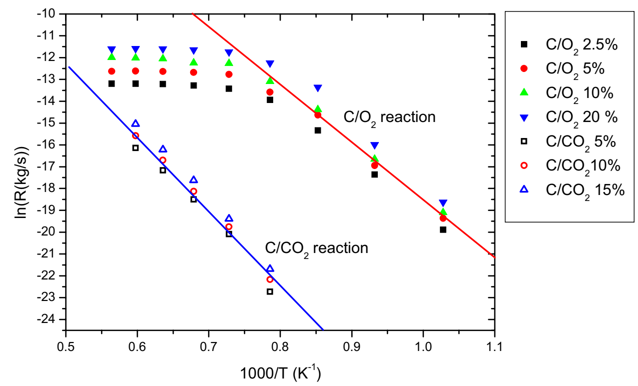

Fig. 6. Comparison between C/CO_2 reaction and C/O_2 reaction

Next Quarter Activities

- Preparing for moisture effect test
- Finalization of burn-off effect test

Issues/Concerns:

There are neither issues nor concerns.

<u>Task 4-1:</u>

Implementation of Molecular Diffusion (INL)

Task Status and Significant Results

Several models for calculating heat transfer and chemical reactions in Very High Temperature Gas-Cooled Reactors (VHTRs) were implemented into the latest authorized version of the

ATHENA code (RELAP5-3D 2002, Siefken et al 2003). The implemented models include (1) model for calculating the effective thermal conductivity of the core and reflector regions of pebble bed VHTRs, (2) model for calculating effective thermal conductivity of the core and reflector regions of block-type (prismatic) VHTRs, (3) model for calculating flow losses in pebble bed VHTRs, (4) models for calculating convective heat transfer in pebble bed and block-type VHTRs, (5) models for calculating chemical reactions and mass transfer in reflector and core regions of pebble bed and block-type VHTRs following ingress of air or water vapor, and (7) models for calculating transfer of decay heat in reactor core to the ultimate heat sink during a conduction cooldown accident. The models were implemented into Version 2.20 of the ATHENA code. The implementation followed the rigorous configuration control and quality assurance procedures required for residency in versions of ATHENA authorized for release and general application.

In addition to the work described above, several models for calculating various aspects of behavior of High-Temperature Gas Reactors (HTGRs) will be implemented into the version of RELAP5, representing all of the noncondensable gases produced in an HTGR during an accident. The aspects of behavior calculated by these models include (1) chemical reactions of oxygen, water and carbon dioxide with graphite in HTGRs, (2) effective thermal conductivity of heterogeneous cores of HTGRs, (3) flow losses and convective heat transfer in HTGR, and (4) transfer of decay heat by radiation, conduction, and natural convection from the outer surface of the reactor core to the ultimate heat sink.

Next Quarter Activities

Implementation of modeling for chemical reactions into latest officially released version of RELAP5/ATHENA.

Issues/Concerns:

No issues or concerns.

Task 4-2:

Improvement of System Code (INL)

Task Status and Significant Results

The MELCOR computer code (version 1.8.5) was assessed using natural circulation data generated in the NACOK experimental apparatus (Kuhlmann 2002). This is the same data that was assessed using the RELAP5-3D computer code as reported in the 2004 annual INERI report INEEL/EXT-04-02459 (November 2004).

The MELCOR model contained the same number of control volumes and heat structures as used in the RELAP5 model, (same dimensions) thus a direct comparison of the RELAP5 and MELCOR 1.8.5 results could be made. A description of the geometry and boundary conditions used in the model are contained in INEEL/EXT-04-02459. Preliminary results of the comparison are show in Fig. 7.

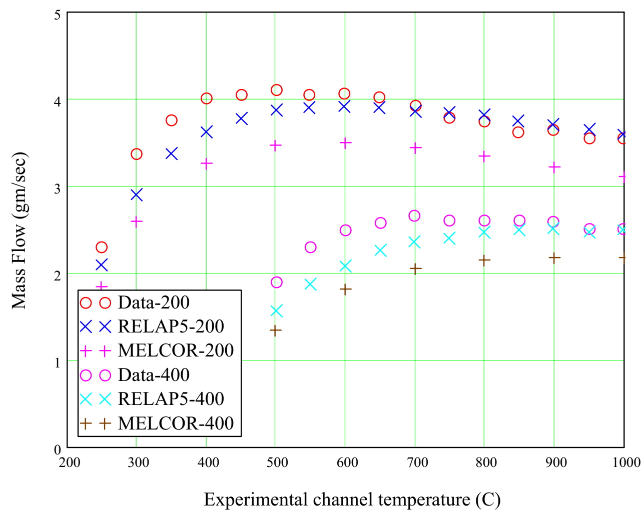

Fig. 7 Measured and calculated air flow rates for the NACOK natural circulation experiment corresponding to return tube temperatures of 200 C and 400 C

Preliminary assessment of the results indicate that the convective heat transfer coefficients calculated by MELCOR in the return tube are slightly low than the ones calculated by the RELAP5 code thus, resulting in lower mass flow rates as seen in the figure. The lower heat transfer coefficients result in less heat loss from the air, resulting in higher gas temperatures in the return tube which in turn affects the net buoyancy force driving the experimental flow rate. A comparison of the natural convection correlations in RELAP5 and MELCOR will be done and reported next quarter.

Next Quarter Activities

Continue to validate the MELCOR code against the SNU-RCCS data

Issues/Concerns:

There are neither issues nor concerns.

Task 5:

Neutronic Modeling (University of Michigan)

Task Status and Significant Results:

In an effort to obtain a preliminary estimate of fission product (FP) decay heat deposition in the VHTGR core following reactor shutdown, we have initiated coupled MCNP5 neutron-photon transport calculations. The calculations have been performed with homogenized fuel assemblies grouped into three annular regions, for a total of 30 fuel segments. We have performed coupled neutron-photon transport calculations to date for a beginning-of-cycle (BOC) core without T/H feedback effects, with the primary purpose to validate the methodology. Together with these neutron-photon MCNP5 calculations, we have obtained with the ORIGEN2.2 code a preliminary estimate of the inventories of key FPs as a function of fuel burnup. We have, however, decided first to perform a simplified calculation for decay heat deposition based on the BOC MCNP5 calculations, while we develop a more accurate methodology for full time-dependent FP decay heat calculations accounting for both betas and gammas for the VHTGR core. In this approach, we have obtained a preliminary estimate of FP decay heat deposition rates in each fuel assembly by combining the *spatial* distribution of gamma deposition rates in the core, from the MCNP5 coupled neutron-photon calculations, with the ANS-5.1 decay heat curve for *time-dependent FP evolution*.

Next Quarter Activities

- Complete MONTEBURNS fuel depletion calculations with 30 fuel segments.
- Develop a method to represent in MCNP5 gamma transport analyses the actual gamma and beta energy releases from key fission products from ORIGEN2.2 fuel depletion calculations.

Issues/Concerns:

There are neither issues nor concerns.

Task 6:

Validation and verification

Part of results shown in this report are part of V&V. This activities will continue.

There are no concerns.

Project Milestone/Deliverable Summary:

Milestone/Deliverable Description	Planned Completion	Actual Completion
1. CFD TH Code Development	30 June 2005	completed
1-1 CFD TH model	31 December 2004	completed
1-2 Diffusion model	31 December 2003	completed
1-3 Chemical reaction model	30 June 2005	completed
1-4 Particle model	30 June 2005	completed
2. RCCS Separate Experiment	30 June 2005	completed
2-1. Development of water-pool RCCS	31 December 2003	completed
2-2. Scaling of water-pool RCCS	30 June 2004	completed
2-3 Heat transfer coefficients	30 June 2005	completed
3. Air Ingress Separate Experiment	30 June 2005	completed
3-1. Measurement technique development	30 June 2004	completed
3-2. Diffusion-limited model	30 June 2005	completed
4-1. Implementation of Diffusion model	31 March 2005	completed
4-1-A. Noncondensable gas implementation	30 April 2003	completed
4-1-B Diffusion model	31 December 2003	completed
4-1-C Simulation	31 March 2005	In progress
4-2. Implementation of Chemical Equilibrium Model	31 December 2003	completed
4-2-A. Simulation	31 March 2005	In progress
5. Neutronic Modeling	31 December 2005	In progress
6. V&V Simulation	31 December 2005	In progress
6-1. RCCS validation	31 December 2005	In progress
6-2. System code vs. CFD code	31 December 2005	In progress
6-3. Large-scale air ingress analysis	31 December 2005	In progress
6-4. System-scale simulation	31 December 2005	In progress

*** This task was not initiated due to the funding delay.